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FINAL REPORT

STUDY OF THERMOELECTRIC COOLING OF ELECTRONIC EQUIPMENT

Contract NAS8-18026

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FOREWORD

This document is the final report on the "Study of Thermo-Electric Cooling of Electronic Equipment" performed for the Astrionics Laboratory, Marshall Space Flight Center, National Aeronautics and Space Administration, Redstone Arsenal, Alabama by the Lockheed Missiles & Space Company's Huntsville Research & Engineering Center.

The work was performed under Contract NAS8-18026. Technical Supervisor for the contract was Mr. Walter Kaspereck of the Astrionics Laboratory.

SUMMARY

The objectives of this study were threefold: investigation and test of thermoelectric coolers; the utilization of these thermoelectric elements in the cooling and temperature stabilization of electronic components; and the generation of a thermoelectric design manual. All the objectives have been achieved.

Several thermoelectric coolers were chosen from different producers based on their heat transfer capacities, temperature differentials, coefficients of performance and sizes. These units were carefully tested and the data obtained compared with the manufacturer's published data. These tests showed clear performance differences among the producers of the thermoelectric elements. In general the quality of the units as measured by the coefficient of performance varied directly with the cost of the unit.

An electronic mockup device for cooling electronic components was designed, fabricated and tested. This unit performed as expected. A temperature stabilization chamber and a switching-type temperature control circuit were developed, designed, fabricated and tested for a 0° to 100°C ambient temperature environment. The temperature inside the chamber was held to within 1.0°C of the initial setting (50°C).

The thermoelectric design manual has been completed and is included as a supplement to this report.

CONTENTS

1.0 TECHNICAL DISCUSSION

1.1 BACKGROUND

The main objective of this project was the generation of a thermoelectric design manual for the cooling of electronic components. In general there are two instances when conventional methods of cooling are not effective in the design of electronic system packaging as follows:

1. Heat must be removed from a hot spot or temperature-sensitive component and transferred to a heat sink which is at the same or even at a higher temperature than the spot being cooled, i.e., the heat must be pumped "uphill."

2. A temperature-variable component must be stabilized at a single temperature for system stability, but because of leakage currents, high temperature stresses, etc., the control temperature must be lower than the maximum ambient.

Examples of the above are:

1. For a 1 watt load, the designer selects a transistor rated at 5 watts at 25°C, derated linearly to zero watts at 125°C. For the device to dissipate the required 1 watt the temperature must not exceed 105°C but the heat sink may be at 125°C. A thermoelectric device is the only practicable way to absorb heat at 105°C and dispose of it at 125°C.

2. The matched pair input stage for a high gain amplifier is matched at 25°C. Oven stabilization at the maximum ambient temperature would result in excessive leakage current. A heater/cooler is required to hold a 25°C chamber temperature while the ambient varies from -20°C to +125°C. This can be achieved by placing the temperature-sensitive component in an insulated chamber with a thermoelectric element. Since the thermoelectric unit can operate as a cooler or heater, the temperature in the chamber can be stabilized by using a temperature sensing device and a control circuit. The proper heat transfer design using thermoelectric elements is given in basic steps in the design manual.

1.2 BASIC REVIEW OF THERMOELECTRIC COOLER THEORY AND OPERATION

The thermoelectric family of devices operates on the interrelationship between electrical and thermal energy. The thermocouple often utilized for temperature measurement is based on this interrelationship. When two dissimilar metals are joined to form a loop, a voltage is generated proportional to the temperature difference between the two junctions. This is called the Seebeck effect.

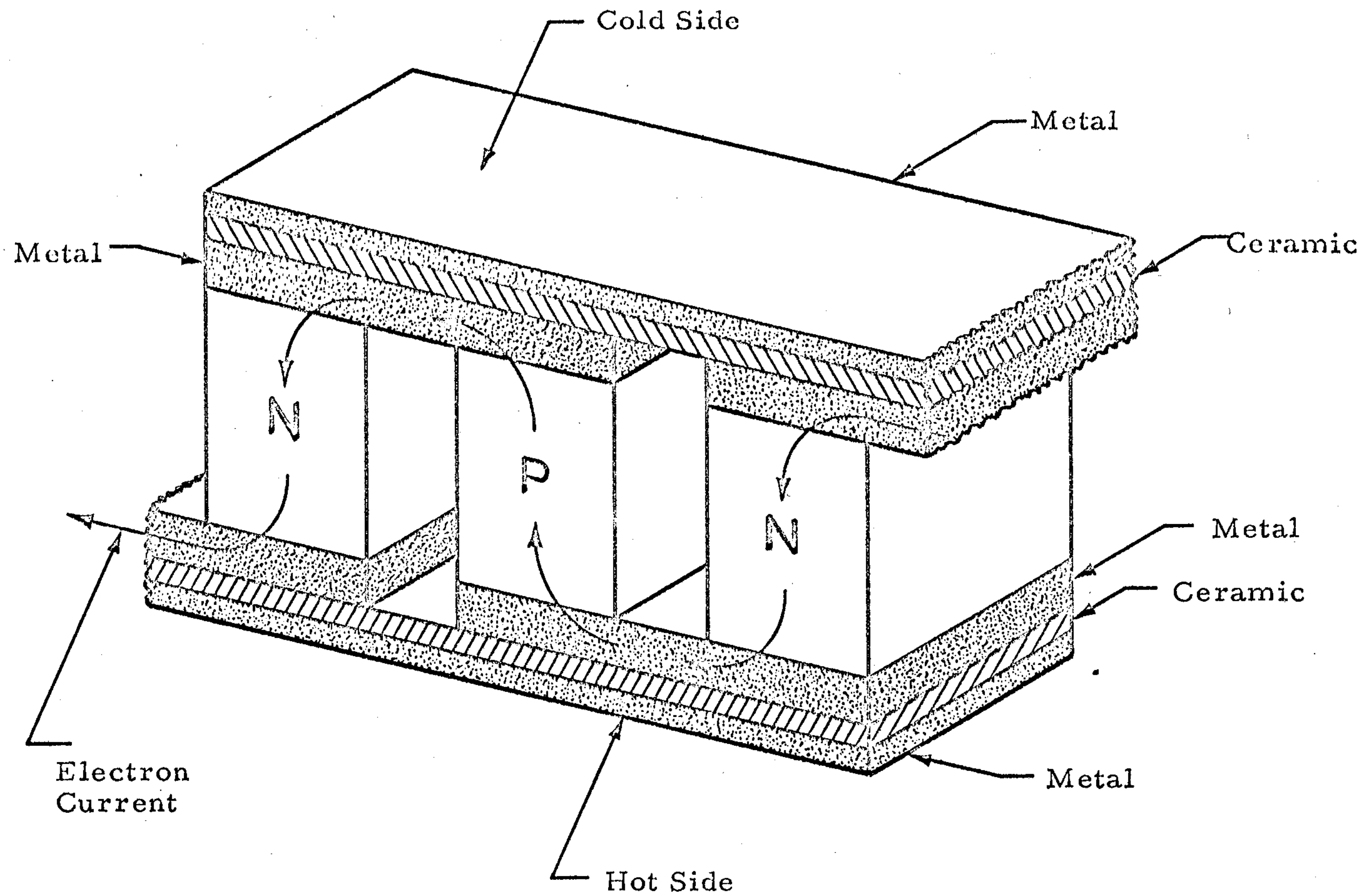
Another effect caused by this interrelationship between electrical and thermal energy was discovered by Peltier. If two dissimilar metals are joined, an electrical current passing through the junction causes the junction to release or absorb heat depending upon the direction of current flow. It was determined by Lord Kelvin that the Seebeck and Peltier coefficients are directly proportional to the absolute temperature.

The transfer of large amounts of thermal energy (heat) to or from a junction by the Peltier method using dissimilar metals is not feasible because the thermal conductivity of metals is high. Thus, most of the heat transferred from the cold to the hot junction by the Peltier effect will be lost through internal thermal conductivity. If an insulator is used instead of a metal, more heat (I^2R) would be lost in overcoming the resistance of the material than would be transferred. A material is required which has both a low resistance to electrical current and a low thermal conductivity.

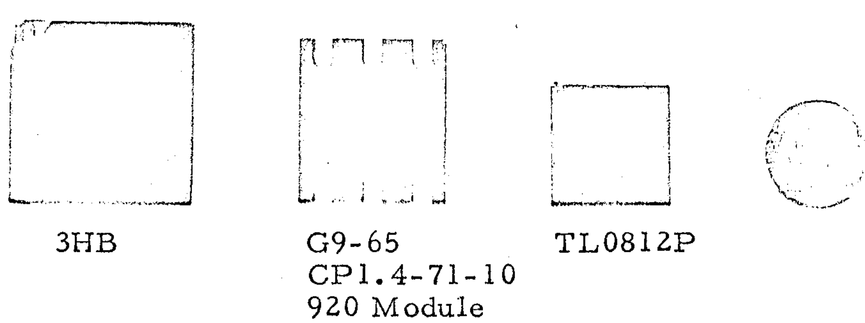
This can be achieved by starting with a semiconductor and diffusing into it a material with one more or one less electron in its outer orbit. This has the effect of greatly decreasing the electrical resistance of the material while simultaneously decreasing the thermal conductivity. The electrical resistance decreases because of the increase in excess electrons or holes available for current flow. The thermal conductivity is decreased because the addition of foreign atoms causes discontinuities in the semiconductor which increases its thermal resistance. The increase in thermal conductivity caused by the additional free electrons is overshadowed by the decrease in thermal conductivity due to the greater number of discontinuities.

The basis of operation of a Peltier thermoelectric heat pump can be seen from Figure 1. The N material consists of a semiconductor diffused with another material which has one more electron in its outer shell. The P material consists of the same semiconductor diffused with a material which has one fewer electron in its outer shell. Because of this electron unbalance the N type material is at a higher energy level than the P type material.

Referring to Figure 1, electron current flows into the P material at the hot side and into the N material at the cold side. Since the N material is at a higher energy level than the P material, the electron gains energy in an P to N transition. It gains this thermal energy from the thermoelectric device by absorbing heat from the cold side. If the battery connections were



THERMOELECTRIC HEATER COOLER
INTERNAL CONSTRUCTION
FIGURE 1A



RELATIVE SIZES OF
THERMOELECTRIC HEATER-COOLERS

FIGURE 1B

reversed, the electron would give up energy to the cold side as heat in going from a higher to a lower level of energy.

The quantity of heat the thermoelectric can transfer is

$$Q = \alpha T_c I - 1/2\, I^2 R - K \Delta T \tag{1}$$

α = Seebeck coefficient, Volts/^oK

T_c = cold side temperature, ^oK

I = input electrical current, amperes

R = electrical resistance, ohms

K = thermal conductivity, watts/^oK

ΔT = temperature difference between hot and cold sides, ^oK

There are two sources of heat loss in a thermoelectric device. One is the Joulian heat loss (I^2R) and the other is the heat loss through the thermal conductivity of the thermoelectric material. Since the heat transfer is a function of I, and the Joulian heat loss is a function of I^2, the thermoelectric cooler performs best at a low drive level.

If equation (1) is differentiated with respect to I,

$$\frac{dQ}{dI} = \alpha T_c - IR \tag{2}$$

the maximum value of Q is reached when $\frac{dQ}{dI} = 0$ or $I_{Qmax} = \frac{\alpha T_c}{R}$

substituting into equation (1)

$$Q_{max} = \alpha T_c \left(\frac{\alpha T_c}{R}\right) - 1/2 \left(\frac{\alpha^2 T_c{}^2}{R^2}\right) R - K\, \Delta\, T,$$

if Q = 0, the maximum ΔT that can be obtained is

$$\Delta T = 1/2\, \frac{\alpha^2}{RK}\, T_c{}^2\ , \tag{3}$$

the quantity $\frac{\alpha^2}{RK}$ is called the figure of merit (Z) of the thermoelectric heat pump.

1.3 DESCRIPTION OF TASKS

The first task was the selection of five (5) thermoelectric elements from various producers. These units were selected based on their heat pumping capability, maximum temperature differential, and coefficient of performance. Medium sized units were chosen because NASA/MSFC requirements are in the zero to eight watt range. The cost of the selected units varied from \$10 to \$65 each.

The five units were tested and the data obtained was compared with the manufacturer's data sheets. The test setup is shown in Figure 8. A large amount of insulation was used to insure that the heat leakage from the surroundings was less than 50 milliwatts. The heat load consisted of several resistors whose voltage and current were monitored and controlled externally. The hot side of the thermoelectric cooler was mounted on a heat sink with large fins. This, in conjunction with a fan, was used to maintain the hot side of the thermoelectric device at a constant temperature to insure accurate data. In all five cases, the test data agreed closely with the manufacturer's data. Test data for the five units for constant temperature differentials of 0, 5, 10, 15, 20 and 25°C are plotted on the same graph, Figures 2, 3, 4, 5, 6, and 7, for easy comparison. The figures show that there are wide differences in performance among the five thermoelectric elements. The coefficient of performance, $\left(\frac{\text{thermal heat pumped}}{\text{electrical input}}\right)$, varied directly with the cost of the unit. The test data is shown in the Appendix.

An electronic mockup device for demonstrations of thermoelectric cooling was designed, fabricated, and tested. As shown in Figure 9, this consisted of a chamber surrounded by insulation (polyurethane foam) and held in place by copper sheeting. This device can be used when removing hot spots from electronic equipment. The test data for one of the thermoelectric units is given in Chart I. This mockup can be used for demonstrating the heat pumping capabilities of thermoelectric devices.

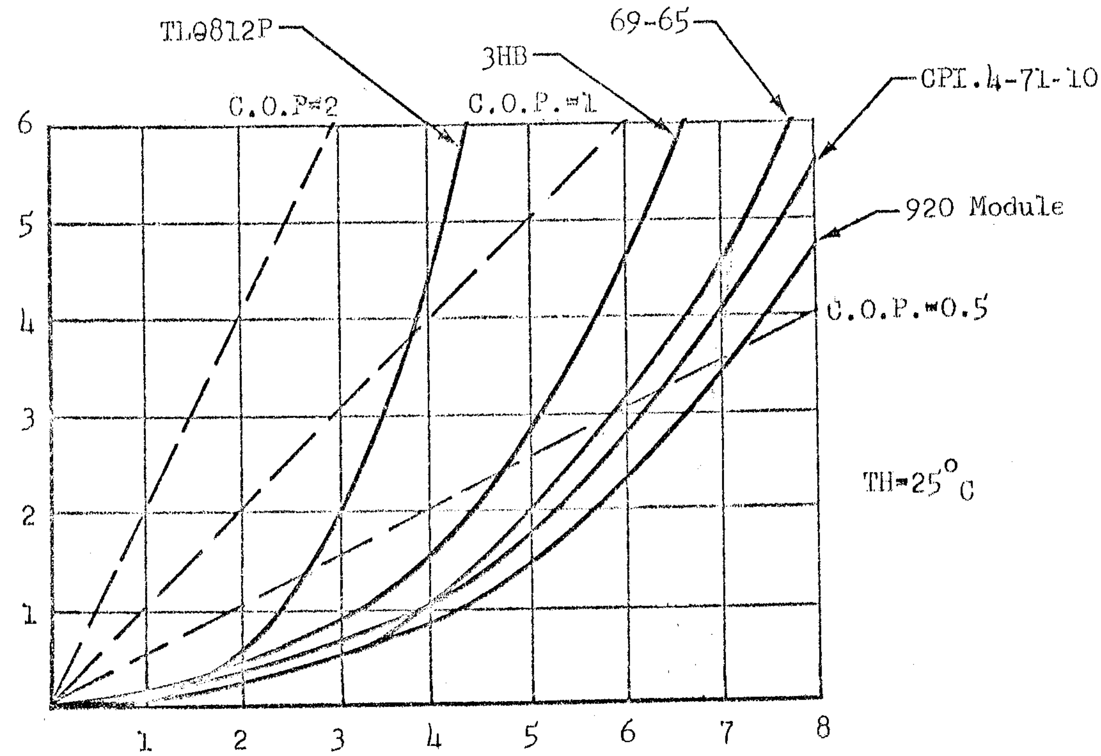
The first portion of Chart I illustrates the effects of hot spot cooling as influenced by the heat sink temperature (T_3) for a fixed input current, the maximum temperature differential (ΔT) which occurs at zero load is a function of the heat sink temperature (T_3). Although the cold side temperature (T_1) rises as the heat sink or ambient temperature (T_3) increases, the thermoelectric cooler becomes more efficient (ΔT increases), as predicted by equation 3 where T_c corresponds to T_1 in Chart I.

In the second part of Chart I the input current was varied while the load and hot side temperature (T_3) were held constant. This shows that the temperature differential (ΔT) increases with an increase of input current (I_{in}). The change in the temperature differential is not a linear function of I_{in} because of the I^2R losses (Equation 1).

In the third portion of Chart I, the load was changed while the hot side and input current were held constant and the cold side (T_1) was allowed to vary. This shows the temperature differential is a function of the load. When the load becomes larger than the thermoelectric cooler can handle at the fixed input current (0.5 amperes), the temperature differential (Δ T) becomes negative. However, the cold side temperature (T_1) is far cooler than it would be without the thermoelectric cooler.

A temperature control circuit was developed, breadboarded and tested for use of the mock-up device in conjunction with a temperature controlled chamber. Since the circuit operates the semiconductors in a saturated or cut-off mode, it is highly efficient. A block diagram and explanation of the circuit operation is given in the appendix. This circuit maintained a 0.1 watt load at 50°C within 1°C over an ambient temperature range of 0°C to 100°C.

From the information and data obtained, a thermoelectric design manual was generated. This manual is included in the appendix and allows a designer to use thermoelectric coolers in the design of electronic equipment without any prior knowledge of thermoelectric devices.



Input Power (WATTS)

Figure 2

THERMAL HEAT PUMPED (WATTS), $\Delta T = 0^{\circ}$

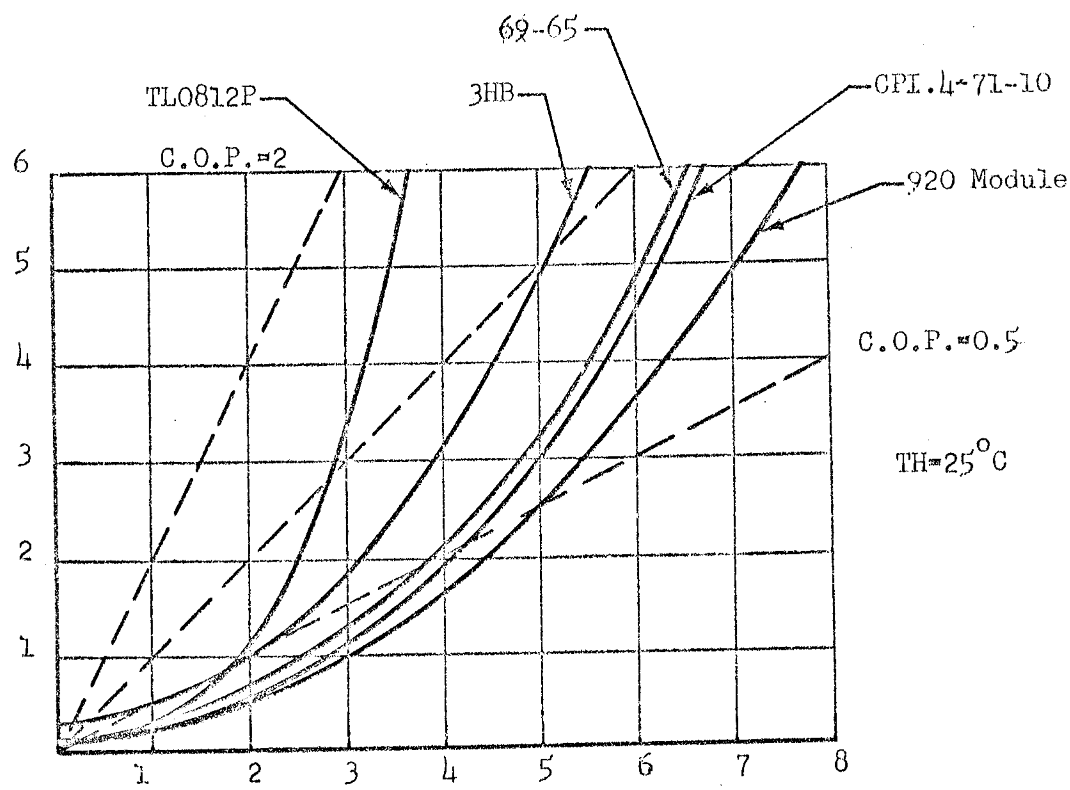


Figure 3

Input Power (WATTS)

THERMAL HEAT PUMPED (WATTS), $\Delta T = 5^{\circ}$

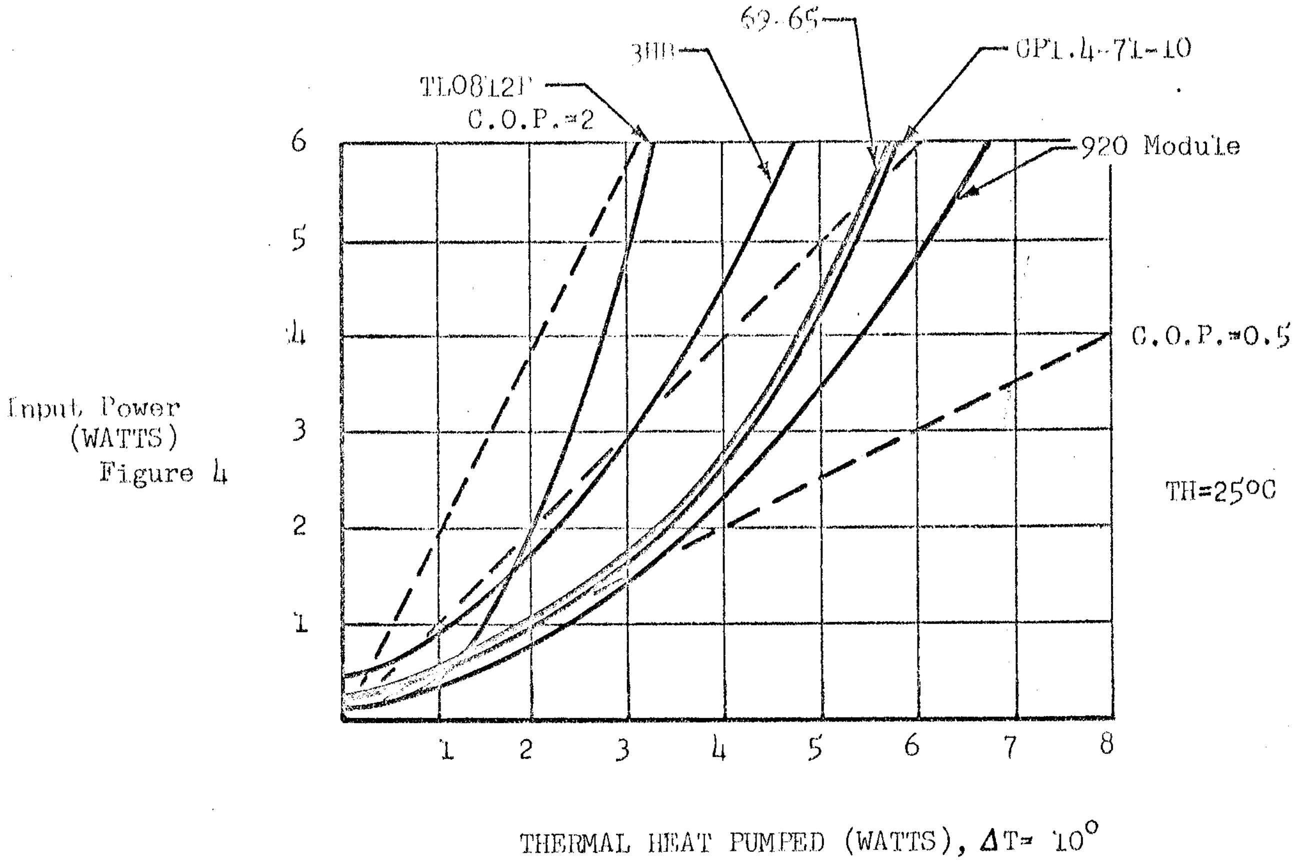


Figure 4

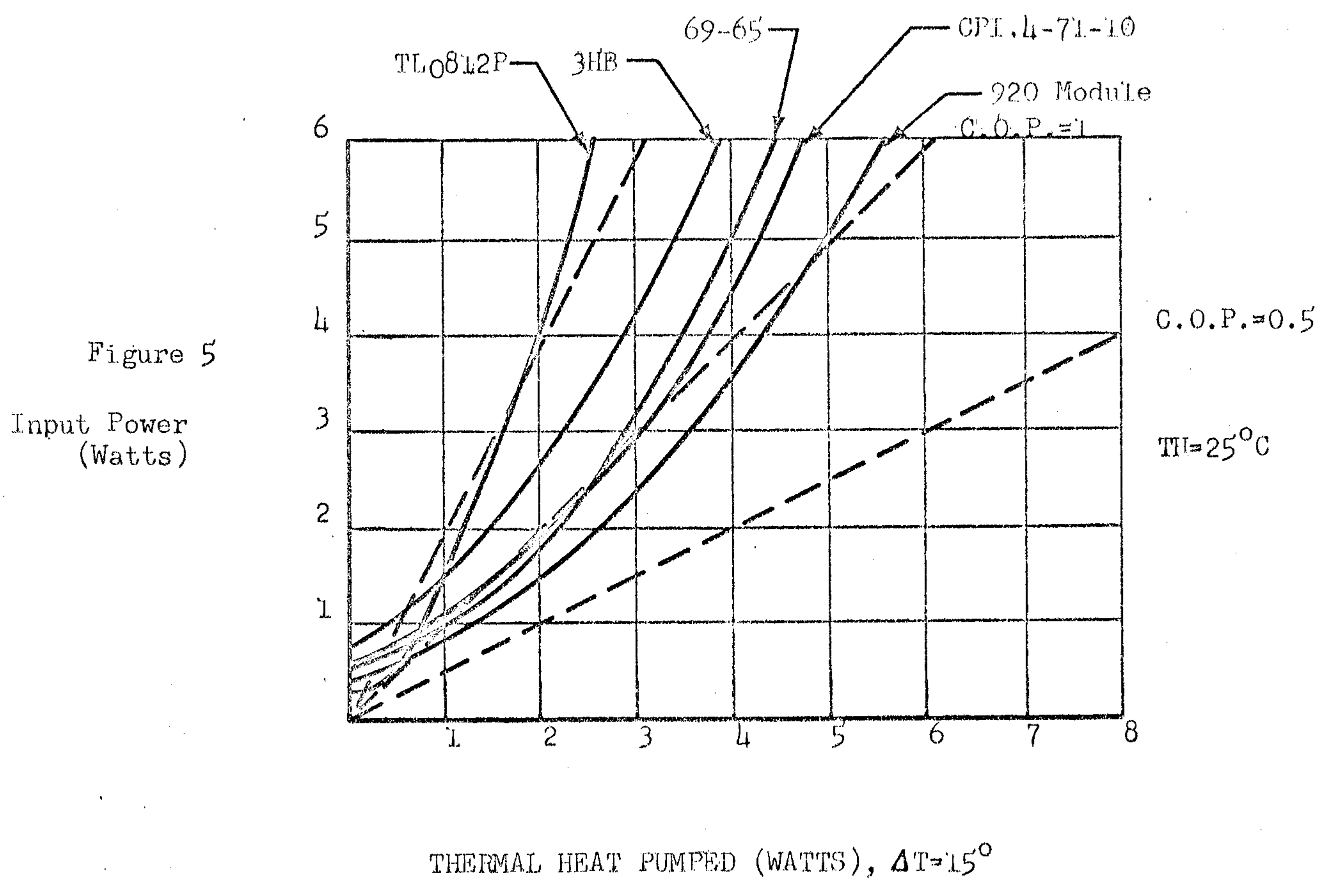


Figure 5

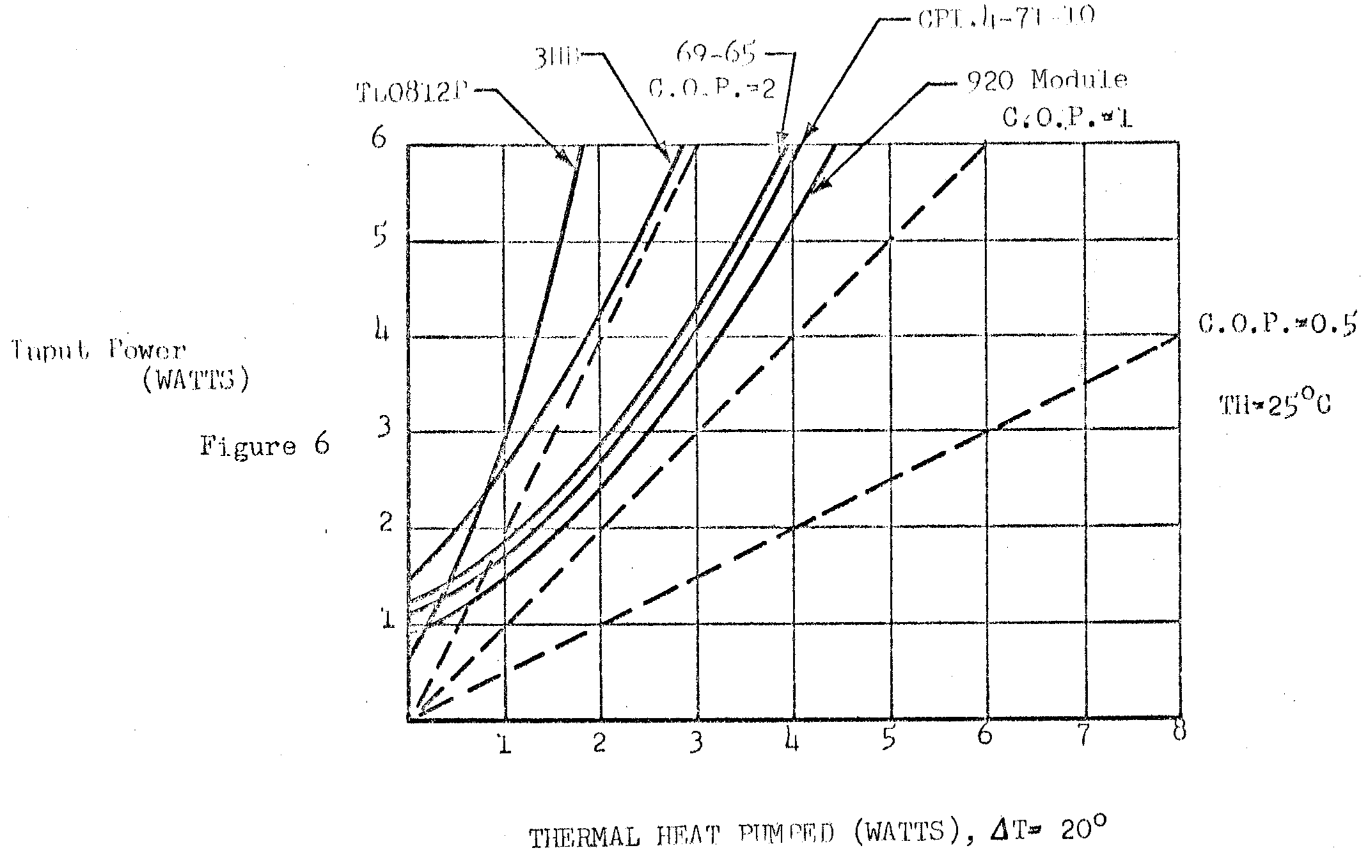


Figure 6

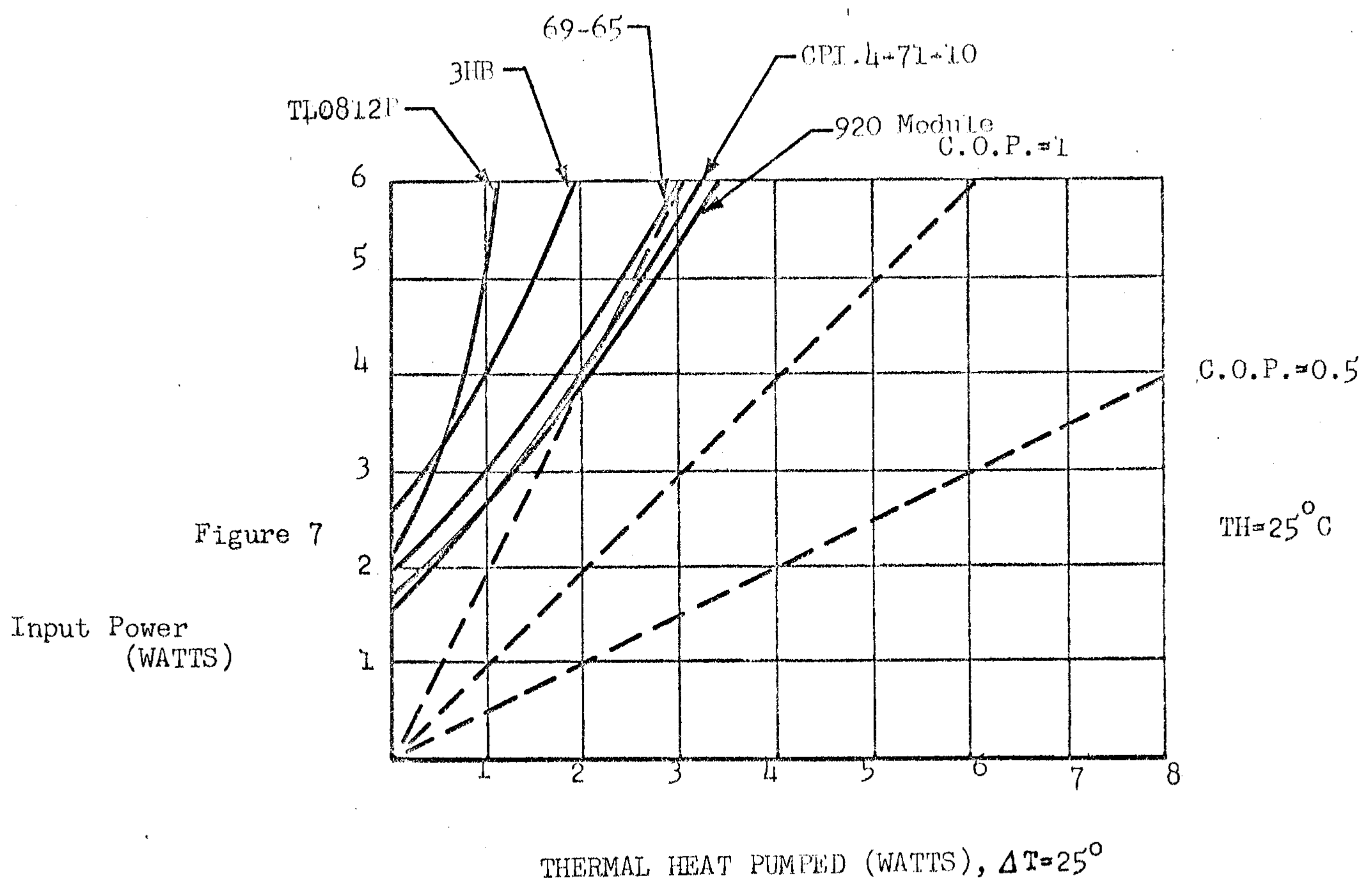
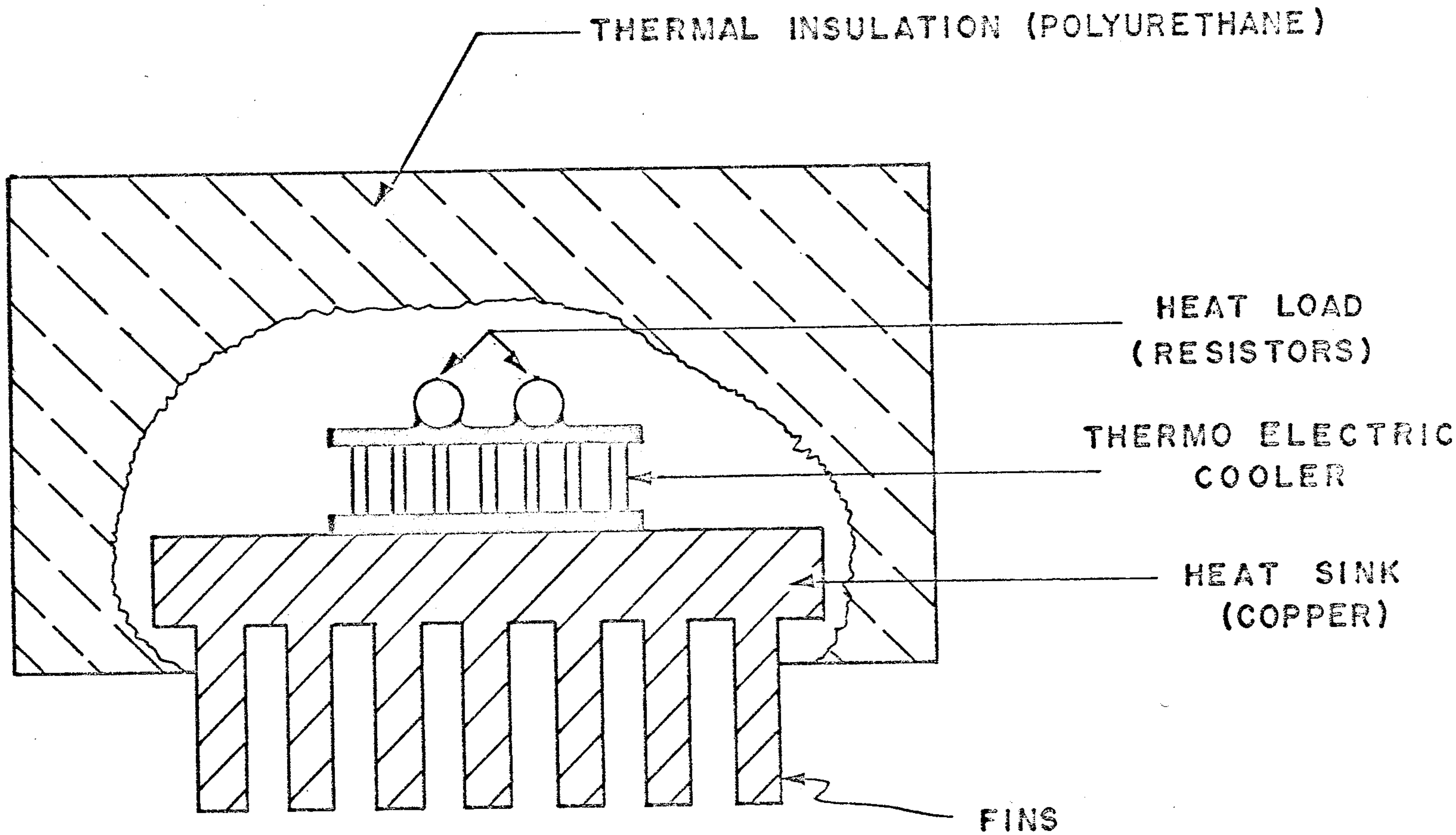
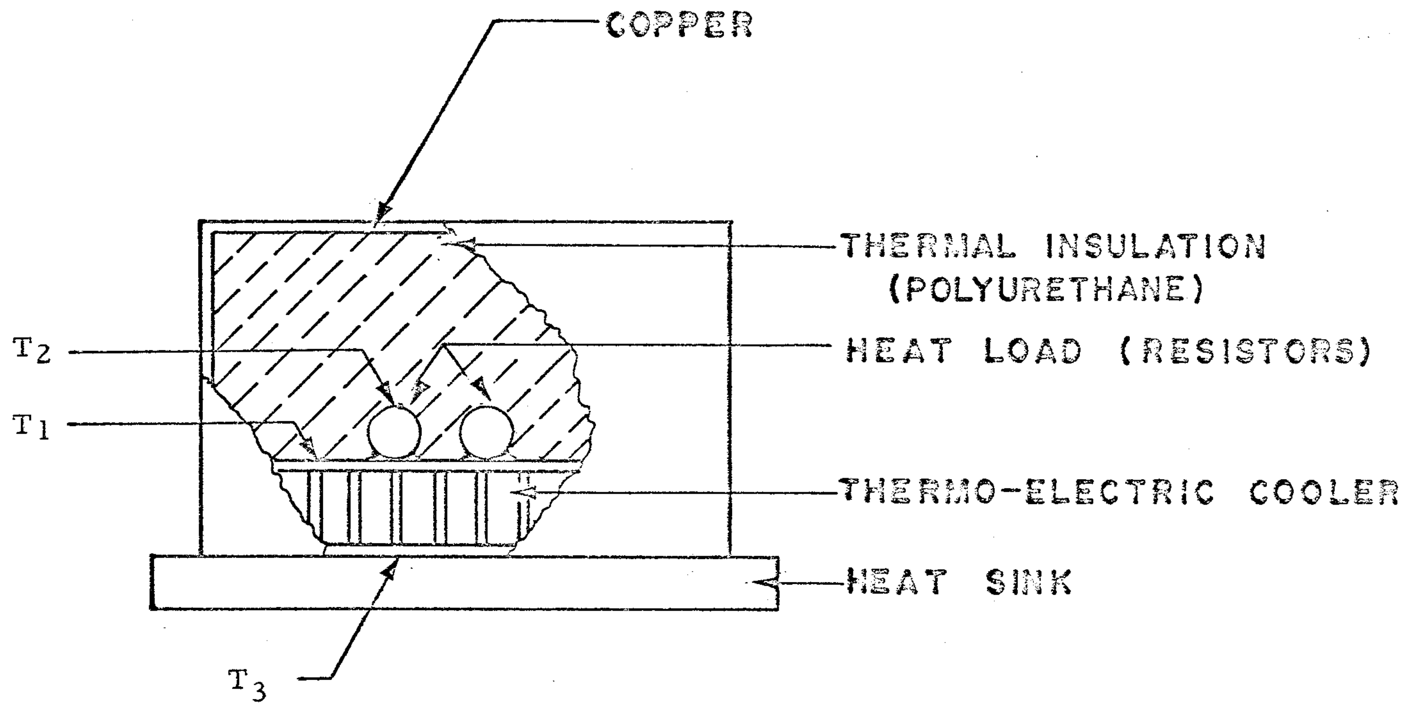


Figure 7



THERMO-ELECTRIC TEST CONFIGURATION

FIGURE 8



CUT-AWAY VIEW OF MOCK-UP DEVICE AND
TEMPERATURE CONTROL CHAMBER

FIGURE 9

CHART I

ELECTRONIC MOCKUP DATA

Independent Variable, T_3 (Heat Sink Temperature)					
I_{in}	Q_{load}	T_1 °F	T_2 °F	T_3 °F	$\Delta T(T_3-T_1)$°F
.5	0	65	65.5	79.5	14.5
.5	0	67.5	68	81	13.5
.5	0	84	85	108.5	24.5
.5	0	93	93.5	121.5	28.5

Independent Variable, Input Current (I_{in})					
I_{in}	Q_{load}	T_1 °F	T_2°F	T_3 °F	$\Delta T(T_3-T_1)$°F
.5	0	66.5	67.5	80.5	14
1.0	0	53	54.5	80.5	27.5
1.5	0	44	46	82	38

CHART I
(continued)

Independent Variable, $Q_{(load)}$					
I_{in}	Q_{load} Watts	T_1 °F	T_2 °F	T_3 °F	$\Delta T(T_3-T_1)$°F
.5	0	65.5	66.5	80.5	15
.5	1	75	78.5	81	6
.5	2	86	93.5	80.5	-5.5
.5	3	96.5	108	82.5	-14
.5	4	107	122.5	84	-23
.5	5	124	146	85.5	-38.5

2.0 CONCLUSIONS AND RECOMMENDATIONS

The use of thermoelectric devices is an excellent approach for either the removal of hot spots from electronic equipment or the temperature stabilizing of temperature-sensitive components. However, they should be used only when more conventional methods of heat transfer are unsatisfactory. Thermoelectric elements must be employed whenever heat must be pumped from a lower temperature to a higher temperature.

As yet, thermoelectric elements have not undergone any extensive or effective reliability program, nor can they withstand the shock and vibration requirements of flight operation. Before these thermoelectric devices are used for other than ground equipment or prelaunch environmental control they must undergo a thorough and stringent reliability program such as has been employed for other devices.

APPENDIX

TO

THERMOELECTRIC COOLER

FINAL REPORT

Section 1

INTRODUCTION

The purpose of this manual is to aid the designer in the application of thermo-electric coolers for the cooling of electronic equipment. Thermo-electric coolers can be used for the temperature stabilization of temperature-critical components or for the removal of hot spots within electronic equipment.

This manual will aid the designer in the selection of the appropriate thermo-electric cooler for his particular requirement. If possible, conventional conduction or convection methods of heat transfer should be employed. However, thermo-electric coolers must be utilized where heat must be transferred from a lower temperature to a higher temperature.

Tests were performed on five thermo-electric units from different producers for comparison with the manufacturer's published data. The test data agreed closely with the published information. The test data for the five units at $\Delta T = 0$ is plotted on the same graph for comparison of their operating characteristics. The manual presents examples of various types of thermal problems which can be solved through the use of thermo-electric elements. Each example is arranged in a step-by-step manner so that the designer may use the manual without any prior knowledge of thermo-electric cooler theory. However, Section 2 pertaining to the theory of thermo-electric phenomena is included for those designers who desire a basic knowledge of the thermo-electric device operation.

Section 2

BASIC PRINCIPLES OF THERMOELECTRIC DEVICES

The basic principles of thermoelectronics have been known since the early 1800's. All thermoelectric devices operate on the interrelationship between electrical and thermal energy.

The initial work was done by Seebeck and Peltier. Seebeck discovered that two dissimilar conductors jointed to form a loop would generate a voltage proportional to the difference in the temperature of the two junctions. This is the principle behind the thermocouple (a device widely used in the measurement of temperatures).

Peltier discovered that a current passed through the junction of two dissimilar metals produces a cooling or heating effect at the junction, depending upon the direction of current flow.

This cooling or heating effect occurs because the electrons of the two dissimilar metals are at different energy levels. When electron current passes from one metal to another, the electron must either gain or lose energy in making the transition. The election gains or loses this energy by absorbing or giving up thermal energy at the junction. Thus, the junction is cooled or heated depending upon the direction of electron current flow.

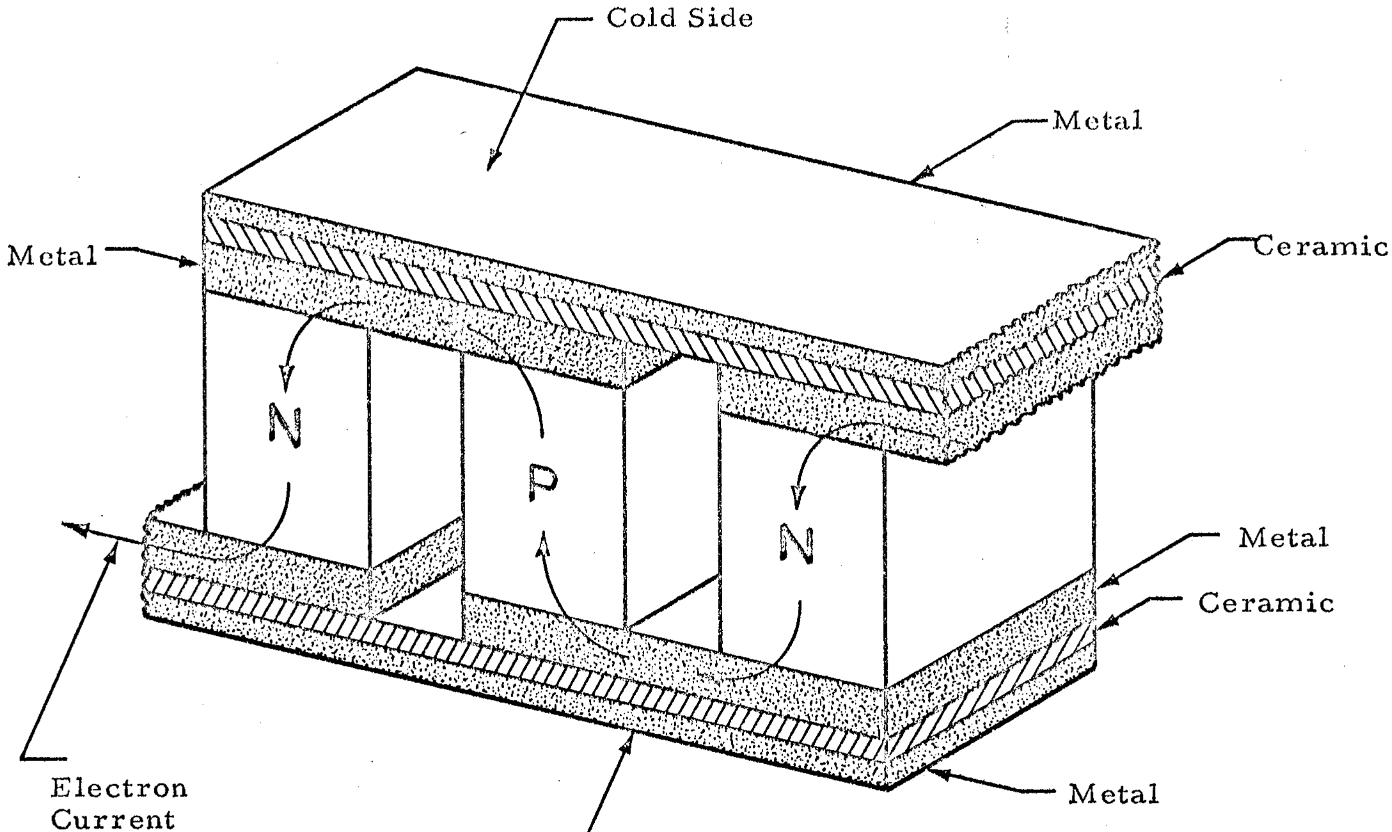
Because of high thermal conduction, a metal cannot be used for efficiently cooling or heating a junction. But if a material with a high electrical resistance (low thermal conduction) were to be used, most of the electrical power would be consumed in overcoming the I^2R losses. Thus, a material is required which has both a low electrical resistance and a high thermal resistance (low thermal conductance).

This type of material was not available until a process for doping semiconductor material was developed. A semiconductor is a material which lies between a metal and an insulator in both thermal conductance and electrical resistance. Doping is a process in which a material which has one more or one less electron in its outer shell is diffused into the basic semiconductor material. If the material has one more electron in its outer shell than the basic semiconductor, it produces an N type semiconductor material after diffusion because an excess of electrons is now present. Conversely, if a material with one less electron in its outer shell is diffused into the basic semiconductor material, a P type semiconductor material is produced because there is now a deficiency of electrons.

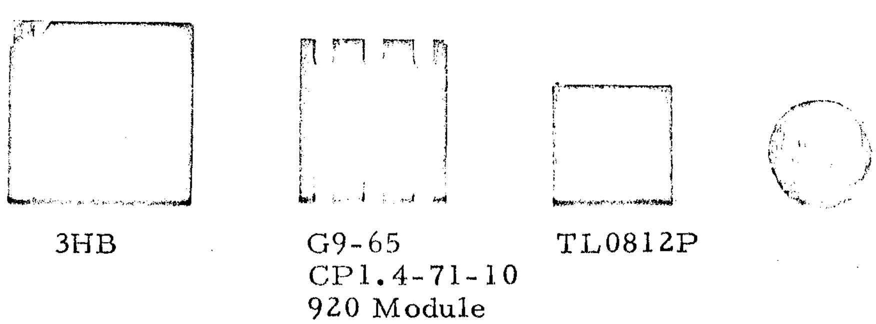
The doping greatly increases the electrical conductivity because of the increase in the number of electrons or holes available for electrical conduction. At the same time, the thermal conductivity is also decreased. This occurs because the foreign material introduced into the basic semiconductor causes discontinuities within the material which decrease the thermal conductance (increase the thermal resistance). Thus, a material with a low thermal conductance and a low electrical resistance is produced. Since the N type material has more electrons than the P type material, the N type material is at a higher energy level than the P type material.

As an electron goes from a P type to an N type material, it must absorb energy in order to jump to the higher energy level. This energy is absorbed from one side of the thermoelectric device. Since heat is removed, the junction decreases in temperature, thus producing the cold side of the thermoelectric cooler. As an electron passes from the N type to the P type material, the same amounts of energy that was absorbed from the cold side must be released, thus producing the hot side of the thermoelectric cooler. Many P-N junctions are joined electrically in series and thermally in parallel to form a thermoelectric cooler. Figure 1A is a diagram depicting typical thermoelectric cooler construction.

Figure 1B is a photograph of three typical thermoelectric units.



THERMOELECTRIC HEATER COOLER
INTERNAL CONSTRUCTION
FIGURE 1A



RELATIVE SIZES OF
THERMOELECTRIC HEATER-COOLERS

FIGURE 1B

The semiconductor material predominantly in use today for thermoelectric coolers is bismuth telluride because it performs best at room temperature (+25°C). New materials are presently under development which will perform best at temperatures below 25°C.

Section 3

THERMOELECTRIC APPLICATIONS AND LIMITATIONS

I. Applications

Thermoelectric coolers can be used for the cooling of electronic equipment as follows:

1. for removing 'hot spots" within the electronic equipment;
2. for maintaining a sensitive electronic component at a temperature lower than it would normally experience; or
3. for temperature-stabilizing a critical, temperature-sensitive component.

Thermoelectric elements should be used in the above situation only if conventional methods of heat transfer cannot satisfy the heat transfer requirements because thermoelectric coolers require electronic circuitry of their own. For example, if the maximum temperature of a transistor can be held within permissible limits by using a small heat sink, then the heat sink should be used instead of a thermoelectric cooler.

Thermoelectric coolers are capable of pumping or transferring heat from a source at one temperature to a sink at the same temperature or at a higher temperature. As the temperature differential (ΔT) between the source and sink increases, the quantity of heat which can be pumped from the source decreases for a given operating current. As can be seen from Figure 2, the maximum quantity of heat is transferred when ΔT equals zero, whereas the maximum ΔT occurs when no heat is transferred.

If required, any thermoelectric cooler can be used as a heater by reversing the direction of the input current flow. This will be necessary if an electronic component has to be stabilized at a temperature which can be either higher or lower than the ambient. Thus, cooling will be required part of the time while heating will be required at other times.

If it is determined that a thermoelectric cooler is required either to remove a 'hot spot" from electronic equipment or to maintain the temperature of an electronic component below its maximum, only a simple control circuit will be required. A temperature sensitive device such as a thermistor will sense the ambient temperature and supply a signal to an electronic switch when the ambient temperature exceeds a preset threshold. The electronic switch will then operate the thermoelectric cooler. When the ambient temperature drops below the preset threshold, the thermoelectric cooler will be turned off.

If it is required to temperature-stabilize an electronic component, a more complex electronic circuit is required. The circuit will then have to operate the thermoelectric unit as a cooler part time and as a heater part time.

II. Limitations

Peltier thermoelectric elements have several operational limits which must be recognized before the elements may be satisfactorily applied.

(1) Temperature Range

A thermoelectric element's normal operating range is 0°C to +100°C; however special units can extend this range to -55°C to +125°C. The upper temperature limit results because the bonds between the semiconductor and the upper and lower plates will be damaged if the upper temperature limit is exceeded. At the lower temperature limit, the coefficient of performance becomes very low thus requiring a large electrical power input in order to pump a small thermal load.

It must be remembered that the power which must be removed from the hot side of the thermoelectric unit is the sum of the thermal heat pumped plus the electrical input power. Thus, it is desirable for the electrical power input to be less than the thermal heat pumped.

(2) Temperature Differential

The normal maximum temperature differential (ΔT) is approximately 50°C although units can be obtained which are capable of handling a small heat load at a 100°C temperature differential. As the temperature differential (ΔT) is increased, the coefficient of performance $\left(\frac{\text{thermal heat pumped}}{\text{electrical input}}\right)$ decreases rapidly. Therefore, it is best to operate a thermoelectric device with as small a ΔT as feasible in order to keep the coefficient of performance high. This is not always possible, as in the case when an electric component must be temperature-stabilized over a wide temperature range environment.

The coefficient of performance varies greatly among manufacturers, and the coefficient of performance increases as the cost of the thermoelectric device increases. For many applications the low cost units can be employed if the heat load and required ΔT are both small.

(3) Vibration and Shock

The thermoelectric elements presently available cannot withstand a high degree of vibration and/or shock. Thermoelectric elements must undergo a high reliability program similar to that performed on conventional electronic components (such as transistors, diodes, capacitors, etc.) before they can be considered flight-approved items.

(4) Reliability

Since no reliability program for thermoelectric coolers has been established, there is very little data available on their expected life (mean-time-between-failure). Some producers indicate an average life of several years if they are operated in a room environment. However, it is not known whether there is any degradation when the thermoelectric unit is operated at or near its maximum or minimum temperature limits.

Section 4

THERMOELECTRIC SELECTION GUIDE

Thermoelectric elements are presently designed to be operated at or near +25°C. They are capable of pumping heat while also maintaining a temperature differential between the component being temperature regulated and the heat sink. However, they are limited in their temperature range, heat load capability and maximum attainable temperature differential.

Before attempting to select a thermoelectric element for your particular application the following questions should be answered and reference made to the page designated to insure that a thermoelectric element can solve your particular heat transfer problems.

QUESTIONS

1. Will the ambient environment be less than 0°C or greater than +100°C?

   if NO, see Page 10, answer 1

   if YES, see Page 10, answer 6.

2. Will the maximum temperature differential (Δ T) exceed 70°C with a heat load in excess of 0.5W?

   if NO, see Page 10, answer 2

   if YES, see Page 10, answer 7.

3. Will a coefficient of performance $\left(\frac{\text{heat pumped}}{\text{electrical input}}\right)$ greater than 2 be required when operating with a temperature differential of more than 10°C?

   if NO, see Page 10, answer 3

   if YES, see Page 11, answer 8

4. If a component is to be temperature-stabilized, must the temperature be stabilized to better than $\pm$ 0.5°C?

   if NO, see Page 10, answer 4

   if YES, see Page 11, answer 9

5. Is small size critical?

   if NO, see Page 10, answer 5

   if YES, see Page 11, answer 10

ANSWERS

1. NO. This temperature range is within the range of thermoelectric coolers available from stock.

2. NO. If the maximum temperature differential is 70°C with a maximum heat load of 0.5W, most of the larger thermoelectric units can satisfy this requirement.

3. NO. Most thermoelectric elements available from stock can satisfy this requirement.

4. NO. This temperature stabilization requirement can be satisfied if the electronic control circuit is properly designed.

5. NO. Since the removal of "hot spots" or the temperature stabilization of critical electronic components will require thermal insulation, a required volume on the order of 2.0" x 2.0" x 1.5" can be expected as a minimum.

6. YES. The normal operating temperature range of thermoelectric coolers is from 0°C to +100°C. Most producers specify an absolute maximum of 125°C for reliable operation. The thermoelectric units can be operated at -50°C if it is realized that the electrical power input required for the same load is approximately 1.6 times that required at 100°C. Also, the maximum attainable temperature differential (ΔT) at -50°C is only approximately 1/4 that attainable at 100°C.

7. YES. The electrical power input to the thermoelectric unit either:

   A. Transfers a large amount of heat from the cold side to the hot side of the thermoelectric device with a small temperature differential ($\Delta T < 1°C$);

   B. Produces a large temperature differential, ΔT, while transferring little heat ($Q < .1W$); or

   C. Transfers heat and also maintains a temperature differential.

   Figure 2 is a graph of Q vs. ΔT for several values of input current. It should be noted that the maximum heat is transferred when ΔT is minimum and that the maximum ΔT is obtained when the heat transferred, Q, is at a minimum. For any current level there is a trade-off between the heat transferred and the temperature differential. Units are available which are capable of maintaining a larger ΔT than 70°C with a heat load of 0.5W but the electrical input power becomes very large. If the electrical input power is not limited, such as in ground equipment, and the electrical losses can be removed from the hot side of the thermoelectric cooler, then this temperature differential limit can be exceeded.

8. YES. (See YES answer (7) to Question 2.) The coefficient of performance, (C.O.P.) is the quantity of thermal heat (Q) transferred divided by the electrical input power. As described above, the heat transferred decreases as the temperature differential, ΔT, increases. For thermoelectric units presently available, a C.O.P. of 2 is maximum for a ΔT of 10°C.

9. YES. The temperature stabilization of a temperature control chamber is basically dependent upon the type of thermoelectric unit, the electronic sensing and control circuits, the thermal load and the thermal losses through the insulation. If the thermoelectric cooler is large enough to handle the heat load (including thermal losses) and the required temperature differential, the temperature stabilization is dependent upon the temperature control and sensing circuitry. Because of stabilization problems within the electronic control circuit, it is best to limit the temperature control to $\pm$ 0.5°C. However, if better temperature stabilization is required, it can be achieved by using a large amount of thermal insulation and careful design of the electronic circuit to prevent oscillations.

10. YES. In general the operation of the thermoelectric elements requires the use of insulation to prevent the loss of heat to the ambient surroundings. This requires space but very little weight. The size of the minimum chamber usually required is approximately 2.0" x 20" x 1.5". This assumes a maximum component size of 1" x 1" x 0.5" and minimum insulation. In most cases the required chamber will be larger than 2.0" x 2.0" x 1.5".

If it was determined after answering the previous questions that thermoelectric coolers can satisfy your heat transfer problems, then the next step is the selection of an appropriate thermoelectric element.

Step 1, Determination of Maximum Heat Load

The first requirement is to determine the maximum heat load to be pumped or transferred. This is found by summing the maximum power dissipated by the electronic components plus the heat leakage into the chamber.

A. The power dissipated by the electronic component can be found by solving one of the following equations:

1. $P = I^2R$

2. $P = VI$

3. $P = V^2/R$

where P = power dissipated by the electronic component (watts)

I = current into the electronic component (amperes) dc or rms

V = voltage across the electronic component (volts) dc or rms

R = resistance of the electronic component (ohms).

B. The heat leakage into the chamber can be found by solving the following equation:

$$Q = \frac{4.56K(\Delta T)(A)}{(L)} \quad \text{(English System)}$$

where Q = heat leakage into chamber (watts)

K = thermal conductivity of the insulating material

$$\frac{(\text{watts})}{(^{\circ}\text{F})(\text{inches})}$$

ΔT = maximum temperature differential between the inside and outside of the chamber ($^{\circ}$F)

A = inside surface area of the chamber in square inches

L = thickness of the insulating material in inches,

or $$Q = \frac{K(\Delta T)(A)}{(L)} \quad \text{(Metric System)}$$

where Q = heat leakage into chamber (watts)

K = thermal conductivity of the insulation material

$$\frac{\text{watts}}{(^{o}\text{C})\ \text{cm}}$$

ΔT = maximum temperature differential between the inside and outside of the chamber (^{o}C)

A = inside surface area of the chamber in square centimeters

L = thickness of the insulating material in centimeters.

The heat losses through the insulation should be kept as small as possible. By summing the maximum component dissipation and the maximum heat loss through the insulation, the maximum heat load of the thermoelectric cooler can be found.

Step 2. If the thermoelectric element is to be utilized for temperature stabilization, the maximum ΔT to be maintained must be found.

The maximum ΔT can be found from the following equation:

$$\Delta T = \left| T_s - T_a \right|$$

where: T_s = the temperature at which the electronic component will be stabilized.

T_a = the highest or lowest ambient temperature, whichever results in the larger value for ΔT.

From the required heat load and the maximum temperature differential a thermoelectric unit can be selected which will perform best under the required conditions by referring to the manufacturers data sheets.

Step 3. Control of Hot Spots

If a hot spot is to be removed or prevented, it is necessary to determine: (a) the amount of heat the component actually dissipates; (b) the heat leakage into the chamber; and (c) the maximum temperature at which the component can safely dissipate this heat.

The heat dissipated by the component and the heat leakage can be found from the equation on pages 12 and 13. The sum of these will be the heat load that the thermoelectric element must pump. Most manufacturer's data on thermoelectric coolers is presented as shown in Figure 2. The electrical input current required for a particular load can be found from the figure. After determining the input current the minimum input voltage can be obtained from the manufacturer's V vs. I curve. When the thermoelectric cooler is used for removing hot spots within electronic equipment, a driving circuit should be used which operates the thermoelectric cooler only when the ambient temperature exceeds a prescribed limit.

Example

Design Specifications:

a. heat load - 3.5 watts by a transistor.

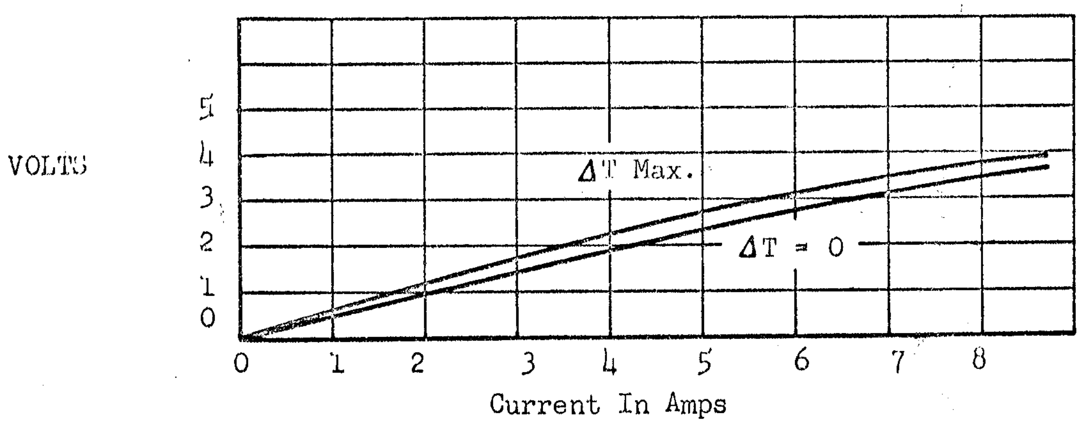
b. maximum temperature the transistor can dissipate this load, $90^{\circ}C$.

c. maximum ambient temperature, $+100^{\circ}C$.

d. input power to be specified.

e. temperature chamber on hand

f. heat leakage into chamber, 0.5W



BORG-WARNER 920 MODULE

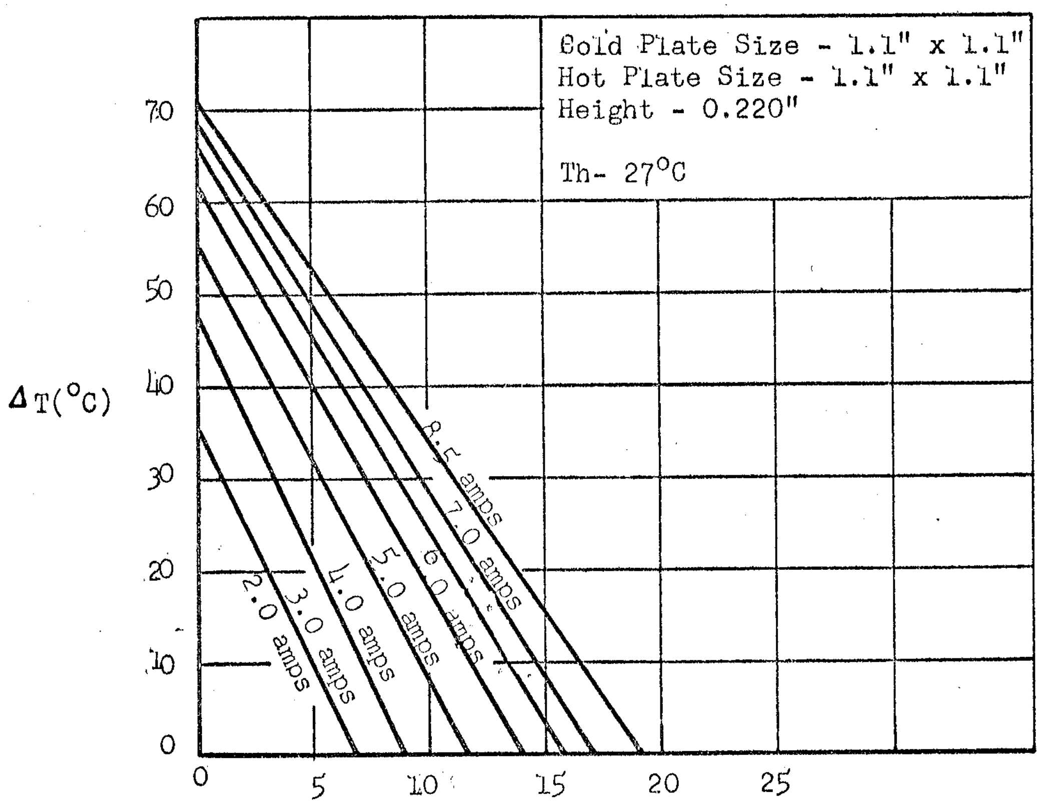


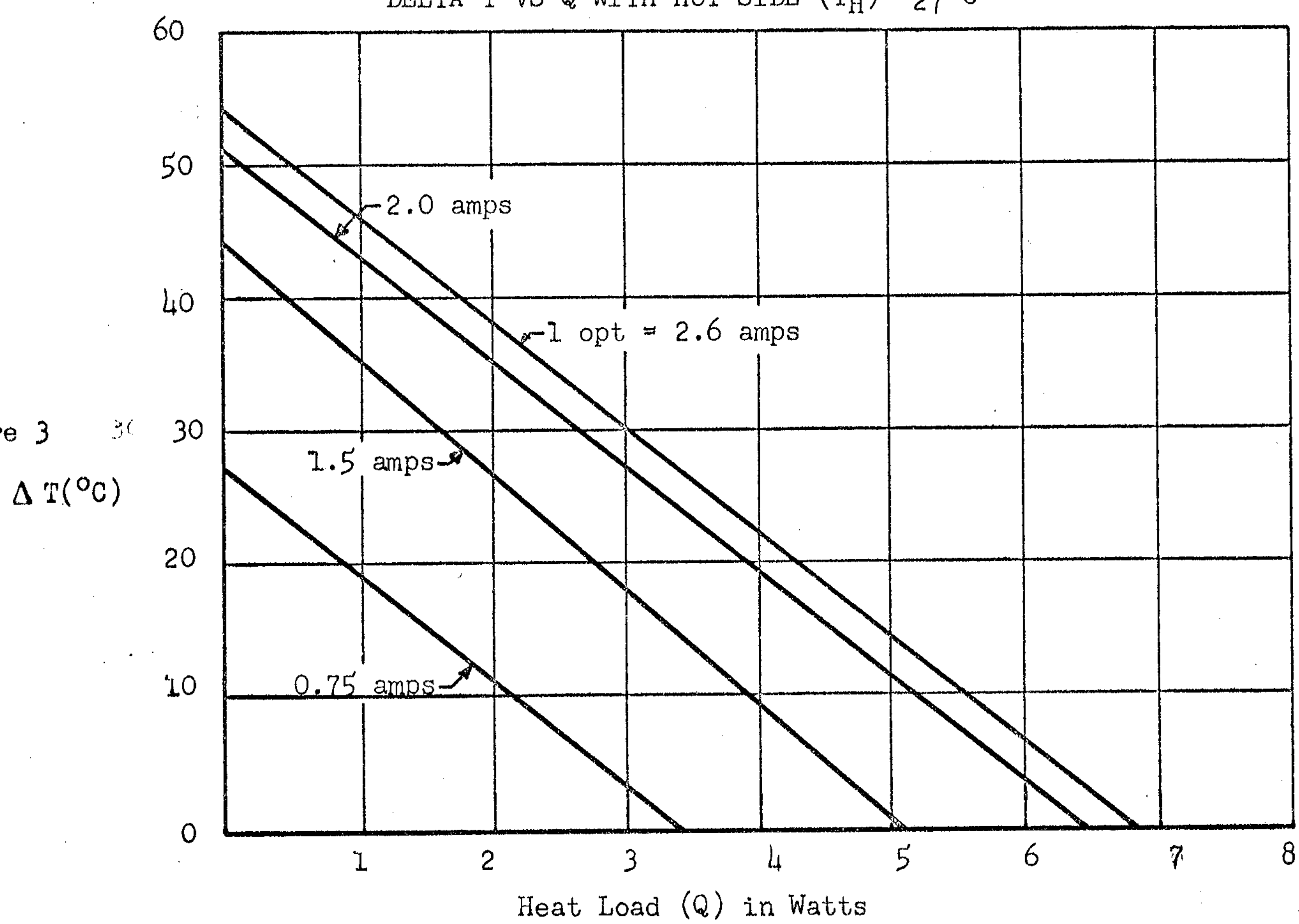
Figure 2

HEAT PUMPED (WATTS)

TL 0812

DELTA T VS Q WITH HOT SIDE (T_H) = 27 C

Figure 3



The total heat load is 3.5W + 0.5W or 4W. The minimum temperature differential is 10°C. In order to insure that the maximum temperature rating of the transistor is not exceeded the inside of the chamber will be designed for a temperature of 80°C. Thus, the thermoelectric cooler will have to pump 4 watts with a temperature differential of 20°C.

Referring to Figure 2, the Borg-Warner 920 module can pump 4 watts across a temperature differential of 20°C with 3.4 amperes input current and an input voltage of 2.0 volts. Thus, the electrical input power is 6.8 watts. The coefficient of performance is

$$\frac{\text{thermal heat pumped}}{\text{electrical input power}} = \frac{4 \text{ watts}}{6.8 \text{ watts}} = 0.59$$

The heat which must be rejected from the hot side of the thermoelectric cooler is 4 watts + 6.8 watts = 10.8 watts.

Figure 3 is the graph of Asarco Thermoelectric Module #TL0812. If this unit were used for the above application, it would require only 2.2 amperes to transfer the same 4.0 watts across a temperature differential of 20°C. The data sheet calls out the thermoelectric cooler resistance at 2.5 ohms. The electrical input power is $I^2R = (2.2)^2 (2.5) = 12W$.

Thus the coefficient of performance is

$$\frac{\text{thermal heat pumped}}{\text{electrical power}} = \frac{4W}{12W} = 0.333$$

The heat which must be rejected from the hot side of the thermoelectric cooler is 4W + 12W = 16 watts

Thus, the Borg-Warner Module #920 coefficient of performance is far superior to the Asarco Module #TL0812 for this application. Also, the heat which must be removed from the #920 module is 10.8 watts whereas 16 watts must be removed from the #TL0812 module. However, the #920 module costs approximately four (4) times that of the #TL0812 module. From these factors the choice of the best thermoelectric cooler for this application can be made.

Step 4. Temperature Stabilization

Thermoelectric elements can be operated as heaters or coolers by simply reversing the direction of the electrical input current. Because of this heating-cooling feature thermoelectric elements can be utilized to stabilize a temperature-sensitive component at or near toom temperature (+25°C) thus reducing thermal stress and extending component lifetime.

A temperature control circuit must be used which operates the thermoelectric element as a cooler or heater depending upon whether the ambient temperature is above or below the control temperature, respectively. It must be remembered that the electrical loss (I^2R) aids the performance of the thermoelectric heater but degrades the operation of the thermoelectric cooler. This can be seen from the equations for the thermoelectric heater and cooler.

$$Q = \alpha I T_c - 1/2 I^2 R - K \Delta T \qquad \text{Cooler}$$

$$Q = -\alpha I T_c - 1/2 I^2 R + K \Delta T \qquad \text{Heater}$$

where

α = Seebeck coefficient, V/°K

I = electrical input current, amperes

T_c = cold side temperature, °K

R = electrical resistors, ohms

K = thermal conductance, watts/°K

ΔT = temperature differential between cold side and hot side.

For the cooler the I^2R losses subtract from the heat pumped (α ITc) and for the heater the I^2R losses add to the heat pumped ($-\alpha$ ITc). Therefore, the temperature at which a component is stabilized should be closer to the highest temperature than to the lowest temperature so as to minimize the temperature differential required when the thermoelectric element is used as a cooler. For example: the ambient environment varies from 0°C to +80°C. Assume that the component can be stabilized anywhere from 15°C to 50°C without degrading performance. The component should be stabilized at 50°C so that a temperature differential of only 30°C is required when the thermoelectric element is cooling even though the heating differential is 50°C.

Example: Design Specifications

a. heat dissipated, 0.5W from critical components

b. control temperature, 50°C

c. Inside chamber size, 4.0 cm x 1.5 cm x 1.5 cm

d. Maximum ambient temperature, 80°C

e. Input power, to be specified

The first step is the design of the temperature control chamber. The inside surface area is 3 (4 cm x 1.5 cm) + 2 (1.5 cm x 1.5 cm) = 18 cm^2 + 4.5 cm^2 = 22.5 cm^2.

A foam insulation is to be used with a thermal conductivity of $K = 0.00026$. From Page 13

$$Q = \frac{K(\Delta T)(A)}{L}$$

It is desired to have a maximum heat leakage of 0.5W. Therefore,

$$Q = 0.5 = \frac{(.00026)(22.5 \text{ sq cm})(30)}{L}$$

$$\text{and } L = \frac{(.00026)(22.5)(30)}{0.5} \approx 0.35 \text{ cm.}$$

The maximum heat which must be pumped by the thermoelectric cooler is 0.5 W + 0.5W = 1W with a temperature differential of 30°C.

If the Borg-Warner Module #920 (Fig. 2) is used, a current of 3 amperes will pump a load of 1 watt and maintain a temperature differential of 30°C. The voltage for a 3 ampere current is 1.7V. Thus, the electrical power is (3) (1.7) = 5.1 watts.

$$\text{The coefficient of performance} = \frac{\text{thermal heat pumped}}{\text{electrical power}} =$$

$\frac{1}{5.1} = 0.196$. The heat which must be removed from the hot side of the thermoelectric device is 1W + 5.1W = 6.1 W.

If the Asarco #TL0182 (Fig. 3) thermoelectric cooler is used, it requires 1.25 amperes to pump 1 watt with a temperature differential of 30°C. The electrical resistance of this device is approximately 2.5 ohms; thus, the electrical power is $I^2 R = (1.25)^2(2.5) = 3.9W$. The coefficient of performance is $\frac{1W}{3.9W} = 0.256$ and the heat which must be removed from the hot side is 1W + 3.9W = 4.9W.

Thus, for this particular application the Asarco #TL0812 is superior to the Borg-Warner #920 module even though it costs only 1/4 that of the #920 module. It can be seen that generalized conclusions should be avoided and the actual operating conditions determined for each module in each application.

Section 5

THERMOELECTRIC DEFINITIONS

DEVICES

Thermoelectric Heat Pump Device: A device which transfers energy from one body to another by the direct interaction of an electrical current and heat flow.

Thermoelectric Device: A generic term for thermoelectric heat pumps and thermoelectric generators.

Thermocouple: A one-couple thermoelectric generator which is used primarily for temperature measurement or control applications.

Thermoelectric Cooling Device: A thermoelectric heat pump which is used to remove thermal energy from a body.

Thermoelectric Heating Device: A thermoelectric heat pump which is used to add thermal energy to a body.

DEVICE CHARACTERISTICS

Coefficient of Performance Of A Thermoelectric Cooling Device: The quotient of the rate of heat removal from the cooled body divided by the electrical power input to the device.

Coefficient Of Performance Of A Thermoelectric Heating Device: The quotient of the rate of heat addition to the heated body divided by the electrical power input to the device.

Junction (In A Thermoelectric Device): The transition region between two dissimilar conducting materials.

NOTE: The Seebeck coefficient of a couple is the algebraic difference of either the relative or absolute Seebeck coefficients of the two conductors.

Peltier Coefficient, Absolute: The product of the absolute temperature and the absolute Seebeck coefficient of the material; the sign of the Peltier coefficient is the same as that of the Seebeck coefficient.

Thermal Conductance: The amount of heat transferred from one side of the thermoelectric cooler to the other in watts/°K.

Electrical Resistance: The steady state resistance of a device. It is given by Vin/Iin and its units are in ohms.

Figure of Merit: The ratio of the Seebeck coefficient squared to the product of the thermal conductivity and the electrical resistance, $\frac{\alpha^2}{RK}$.

EFFECTS IN MATERIALS

Joule Effect: The evolution of thermal energy produced by an electrical current in a conductor as a consequence of the electrical resistance of the conductor.

Joule Heat: The thermal energy resulting from the Joule effect.

Seebeck Effect: The generation of an EMF by a temperature difference between the junctions in a circuit composed of two homogeneous electrical conductors of dissimilar composition; or, in a non-homogeneous conductor, the EMF produced by a temperature gradient in a non-homogeneous region.

Seebeck or Thermal EMF: The EMF resulting from the Seebeck effect.

Peltier Effect: The absorption or evolution of a thermal energy in addition to the Joule heat, at the thermoelectric junction through which an electrical current flows.

Peltier Heat: The thermal energy absorbed or evolved as a result of the Peltier effect.

MATERIAL COEFFICIENTS

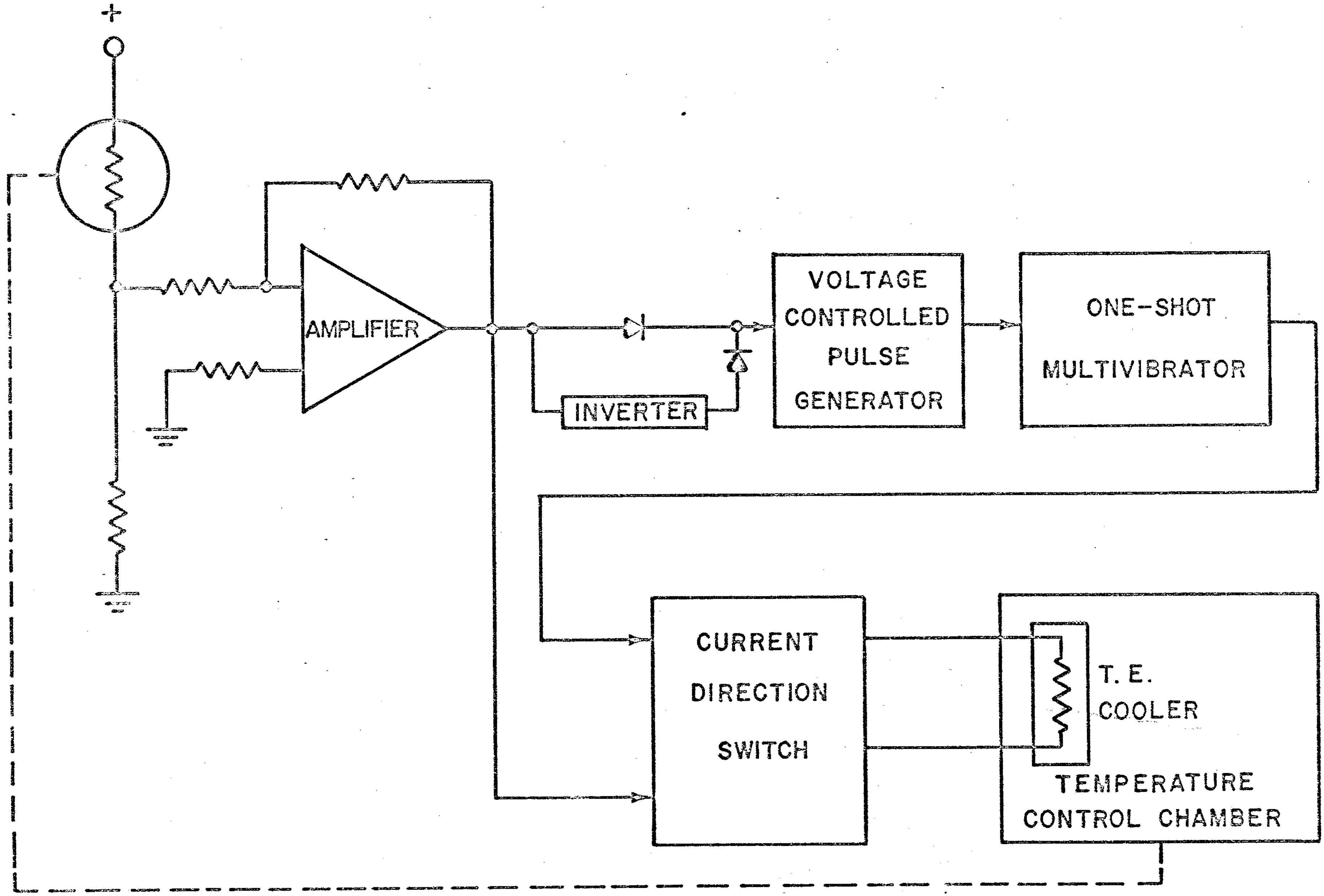
Seebeck Coefficient Of A Couple (For Homogeneous Conductors): The limit of the quotient of the Seebeck EMF divided by the temperature difference between the junctions as the temperature difference approaches zero; by convention, the Seebeck coefficient of a couple is positive if the first-named conductor has a positive potential with respect to the second conductor at the cold junction.

Section 6

TEMPERATURE CONTROL CIRCUIT AND CHAMBER

Figure 4 is a block diagram of a temperature control circuit. The thermistor is located in the temperature control chamber and senses any temperature variation in the chamber. Any error signal from the thermistor is amplified and the amplified signal applied to a voltage controlled pulse generator which emits pulses at a rate proportional to the input signal. These pulses are shaped into equal widths by the one-shot multivibrator. The current direction switch delivers the current pulses to the thermoelectric element in a direction determined by the polarity of the amplifier output signal. Thus the temperature inside the chamber is stabilized. Since the temperature control circuit operates the semiconductors in the cut-off or saturated mode, it has a high efficiency.

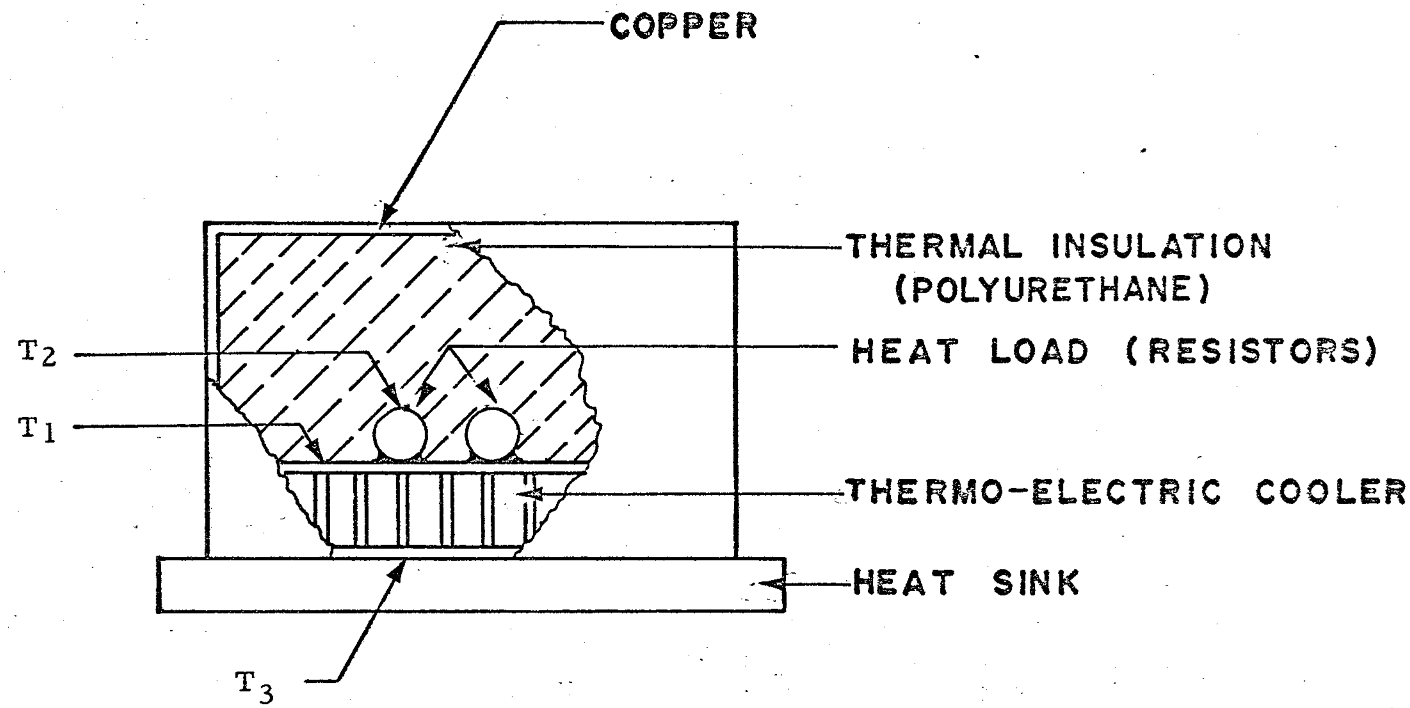
The temperature control chamber is shown in Figure 5. The chamber consists simply of a heat sink, thermoelectric element, a heat load, insulation and copper sheeting to hold the insulation in place. The inside surface area of the chamber should be made as small as possible to keep the thermal losses low. Instead of using a copper box to hold the insulation in place, metal straps can be used effectively. The thermoelectric element must have a good thermal bond between itself and the heat sink. Otherwise, large temperature differentials will occur between the hot side of the thermoelectric element and the heat sink. Since large amounts of heat may need to be removed from the hot side of the thermoelectric cooler, a good thermal bond between the thermoelectric cooler and the heat sink is essential.



BLOCK DIAGRAM

THERMO-ELECTRIC TEMPERATURE CONTROL CIRCUIT

FIGURE 4



CUT-AWAY VIEW OF MOCK-UP DEVICE AND TEMPERATURE CONTROL CHAMBER

FIGURE 5

THERMOELECTRIC MANUFACTURERS

1. Asarco Intermetallics Corporation
   120 Broadway
   New York, New York

2. Energy Conversion, Inc.
   336 Main Street
   Cambridge 42, Massachusetts

3. Frigistors, Ltd.
   5770 Andover Avenue
   Montreal 9, Quebec, Canada

4. International Energy Conversion
   430 Kerby Street
   Garland, Texas

5. Materials Electronic Products Corp.
   990 Spruce Street
   Trenton, New Jersey

6. Ohio Semitronics, Inc.
   1205 Chesapeak Ave.
   Columbus, Ohio

7. Cambridge Thermionics Corp.
   445 Concord Avenue
   Cambridge, Massachusetts

8. Borg-Warner Thermoelectrics
   Wolf and Algonquin Roads
   Des Plaines, Illinois

9. Melpar, Inc.
   3000 Arlington Blvd.
   Falls Church, Virginia

Heat Transfer Test Data

C.PI. 4-71-10 (Material Electronics Products Corporation

			ΔT = 5°C		
I	.5	1	1.5	2	3
V	1.4	2.65	4.0	5.1	7.9
Qin	.7	6	6	10.1	23.7
Qp	2.4	4.75	6.8	8.2	10.25
			ΔT = 10°C		
I	.5	1	1.5	2	3
V	1.5	2.7	4.1	5.4	7.9
Qin	.75	2.7	6.15	10.8	23.7
Qp	1.6	3.8	5.85	7.3	9.3
			ΔT = 15°C		
I	.5	1	1.5	2	3
V	1.54	2.85	4.03	5.3	7.9
Qin	.79	2.85	6.05	10.6	23.7
Qp.	.7	2.75	5.1	6.4	8.3
			ΔT = 20°C		
I	1	1.5	2	3	
V	2.85	4.1	5.3	7.9	
Qin	2.85	6.2	10.6	23.7	
Qp.	2.15	4.15	5.6	7.4	
			ΔT = 25°C		
I	1	1.5	2	3	
V	2.95	4.1	5.35	2.9	
Qin	2.95	6.2	10.65	23.7	
Qp	1.25	3.25	4.6	6.4	
			ΔT = 30°C		
I	1	1.5	2	3	
V	3.07	4.27	5.45	7.9	
Qin	3.07	6.45	10.9	23.9	
Qp	.3	2.3	3.65	5.4	

		$\Delta T = 35^{o}C$	
I	1.5	2	3
V	4.30	5.45	7.9
Qin	6.45	10.9	23.7
Qp	1.3	2.8	4.5

		$\Delta T = 40^{o}C$	
I	1.5	2	3
V	4.34	5.50	7.9
Qin	6.51	11.0	2.39
Qp	.6	1.9	3.65

Heat Transfer Test Data

Energy Conversion Inc. G9-65

$\Delta T = 5^{o}C$

I	.5	1	1.5	2	3
V	.25	.49	.69	.900	1.32
Qin	.125	.49	1.03	1.8	3.96
Qp	.5	1.7	2.75	4	5.6

$\Delta T = 10^{o}C$

I	1	1.5	2	3
V	.51	.717	.940	1.35
Qin	.51	1.07	1.8	4.05
Qp	.75	1.8	3.1	4.75

$\Delta T = 15^{o}C$

I	1.5	2	3
V	.77	.96	1.37
Qin	1.15	1.92	4.11
Qp	.9	2.15	3.8

$\Delta T = 20^{o}C$

I	1.5	2	3
V	.8	.98	1.4
Qin	1.2	1.96	4.2
Qp	0	1.15	2.9

$\Delta T = 25^{o}C$

I	2	3
V	1.02	1.43
Qin	2.04	4.29
Qp	.15	1.9

Heat Transfer Test Data				
Asarco Intermetallics Corp. # TL0812B				
		$\Delta T = 5^{o}C$		
I	.5	1	1.5	2
V	1.21	2.38	3.7	5.06
Qin	.6	2.38	5.4	10.12
Qp	1.2	2.7	3.7	4.25
		$\Delta T = 10^{o}C$		
I	.5	1	1.5	2
V	1.25	2.43	3.7	5.06
Qin	.62	2.43	5.4	10.12
Qp	1.2	2.1	3.1	3.6
		$\Delta T = 15^{o}C$		
I	.5	1	1.5	2
V	1.3	2.45	3.7	5.06
Qin	.65	2.45	5.4	10.12
Qp	.6	1.4	2.4	2.9
		$\Delta T = 20^{o}C$		
I	.5	1	1.5	2
V	1.37	2.5	3.7	5.06
Qin	.66	2.5	5.4	10.12
Qp	0	.8	1.7	2.3
		$\Delta T = 25^{o}C$		
I	1	1.5	2	
V	2.54	3.7	5.08	
Qin	2.54	5.4	10.12	
Qp	.2	1	1.6	
		$\Delta T = 30^{o}C$		
I	1.5	2		
V	3.7	5.06		
Qin	5.4	10.12		
Qp	.3	.85		

Heat Transfer Test Data

International Energy Conversion, Inc. # 3HB

			$\Delta T = 5^{o}C$		
I	.5A	1A	1.5A	2.0A	3A
V	1.05	1.81	2.57	3.0	4.15
Qin	.52	1.81	7.85	6	12.45
Qp	1.25	3.1	4.6	5.7	7.9
			$\Delta T = 10^{o}C$		
I	.5A	1A	1.5A	2A	3A
V	1.10	1.83	2.60	3.0	4.15
Qin	.55	1.83	3.9	6	12.45
Qp	.3	2.2	3.7	4.7	6.8
			$\Delta T = 15^{o}C$		
I	1A	1.5A	2A	3A	
V	1.84	2.54	3	4.15	
Qin	1.84	3.96	6	12.45	
Qp	1.3	2.8	3.8	5.75	
			$\Delta T = 20^{o}C$		
I	1A	1.5A	2A	3A	
V	1.82	2.7	3	4.15	
Qin	1.82	4.05	6	12.45	
Qp	.4	1.9	2.85	4.7	
			$\Delta T = 25^{o}C$		
I	1.5A	2A	3A		
V	2.71	3	4.15		
Qin	4.06	6	12.45		
Qp	1	1.85	3.6		

		$\Delta T = 30^{o}C$	
I	1.5A	2A	3A
V	2.77	3	4.15
Qin	4.07	6	12.45
Qp	.1	1.0	2.5

	$\Delta T = 35^{o}C$	
I	2A	3A
V	3	4.15
Qin	6	12.45
Qp	.1	1.35

Heat Transfer Test Data					
Borg Warner # 920					
$\Delta T = 5^{\circ}C$					
I	.5	1	1.5	2	3
V	.30	.55	.28	1.01	1.56
Qin	.15	.55	1.17	2.02	4.68
Qp	.6	2.25	3.5	4.7	7.1
$\Delta T = 10^{\circ}C$					
I	1	1.5	2	3	
V	.58	.82	1.06	1.55	
Qin	.58	1.23	2.12	4.65	
Qp	1.35	2.6	3.7	5.8	
$\Delta T = 15^{\circ}C$					
I	1	1.5	2	3	
V	.61	.87	1.1	1.58	
Qin	.61	1.30	2.2	4.74	
Qp	.5	1.6	2.8	4.8	
$\Delta T = 20^{\circ}C$					
I	1.5	2	3		
V	.88	1.12	1.61		
Qin	1.32	2.24	4.83		
Qp	.7	1.8	3.7		
$\Delta T = 25^{\circ}C$					
I	2	3			
V	1.16	1.64			
Qin	2.32	4.92			
Qp	.8	2.6			
$\Delta T = 30^{\circ}C$					
I	3				
V	1.66				
Qin	4.98				
Qp	1.4				